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THE RECLAMATION OF ALKALI SOILS

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THE RECLAMATION OF ALKALI SOILS[1, 2]

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INTRODUCTION

THE TERM "ALKALI SOIL" is used in this bulletin to denote soil which contains either an excess of soluble salts or an abnormal amount of absorbed sodium, or both. Hilgard's classification of alkali soils into two types, namely, white alkali and black alkali, will be employed in this publication. White alkali refers to soil which contains an excess of neutral salts, usually chlorides and sulfates. Black alkali refers to soil which contains injurious amounts of soluble carbonate, either with or without chlorides and sulfates. The former type may or may not contain absorbed sodium; the latter always contains absorbed sodium to some extent. The black-alkali type, owing to the presence of soluble carbonate and absorbed sodium, is more alkaline chemically, that is, has a higher pH, than the white-alkali type.

Alkali soils are usually formed as a result of a high water table. The ground water of arid regions commonly contains dissolved salts. The water tends to rise by capillarity and to evaporate, leaving the soluble salts in the soil. By this process large amounts of soluble salts may accumulate in the upper part of the soil. The rate at which salts accumulate in the soil depends upon three factors: (1) the rate of capillary movement of water through the soil; (2) the rate of evaporation; (3) the salt content of the ground water. Obviously, the evaporation of a given amount of a highly saline solution will result in the deposition of a greater amount of salts than the evaporation of an equal volume of a dilute solution.

The occurrence of a high ground-water level depends upon a number of factors. It may be caused by seepage from leaky canals and laterals and by excessive irrigation. For example, there are several hundred thousand acres of farm land in California which were formerly highly productive, but which later became severely injured by alkali brought up by capillarity from a high water table that developed as a result of seepage from canals and the use of excessive amounts of irrigation water. A similar condition exists in many other irrigated areas both in the United States and in other parts of the world. Because of this fact, cer-

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tain authorities have felt that the permanence of irrigated agriculture is doubtful. However, the knowledge that has been gained through recent investigations shows quite clearly that irrigated soil need not necessarily be short-lived. In fact, there is a good reason for the belief that, if the drainage conditions are kept favorable, the maintenance of crop production on irrigated soil depends on essentially the same principles, and can be fully as permanent, as on nonirrigated soils in humid climates.

The soil may also become injuriously saline in consequence of floods that overflow the banks of streams, or by the deep penetration of flood waters through the porous beds of streams. In such cases the level of the ground water in the adjacent valleys may be caused to rise excessively. Later, evaporation may bring about the development of high salinity in the soil. A good example of this mode of alkali accumulation in the soil was found in certain localized spots below Anaheim, California, after the heavy floods of January, 1916, when the Santa Ana River overflowed certain parts of this area and caused the ground water to rise much above the normal level.

Another factor, thought by certain soil scientists[13][4] to be essential to the development of alkali soil, is the occurrence of an impervious stratum in the subsoil, the presence of which prevents deep penetration of excess water and makes possible a high ground-water level where none would otherwise exist.

The reason why a high water table is conducive to the formation of alkali soil in arid climates, whereas this is not the case in humid climates, is threefold: (1) ground waters in arid regions usually contain very much more dissolved salts than in humid climates; (2) the rate of evaporation is much greater in arid climates; (3) the precipitation in arid regions is insufficient to leach the soluble salts, which rise during the periods of intensive evaporation between rains, back into the ground waters whence they came. Consequently, the soil of dry regions tends to become increasingly saline as long as the ground water remains within capillary reach of the evaporation surfaces.

The imminence of the danger from a high water table depends in considerable measure on the type of geological formation from which the runoff drains to lower levels. The reason why this is true is that different kinds of geological deposits contain widely different amounts of salts capable of being dissolved and leached to lower parts of the watershed. Generally speaking, the runoff from granitic deposits is relatively free from dissolved salts; whereas streams which originate in or pass through

[4] Superscript numbers in parentheses refer to "Literature Cited" at the end of this bulletin.

shales or similar deposits are likely to contain considerable dissolved salts, which they carry down to the lower positions.

The application of saline irrigation water may also increase the salinity of the soil,[7] but, as far as the production of alkali soil is concerned, this now appears to be of minor importance, particularly if the drainage conditions are good. Under certain conditions, however, the salinity of irrigation water may contribute substantially to the development of alkali conditions in the soil. For example, when the salts of the irrigation water are composed too largely of sodium compounds, particularly if sodium carbonate or bicarbonate is an important constituent of the water, the continued application of such water may cause serious injury to the soil through the adverse chemical and physical effects that will be produced in the soil.[2, 11] Or if the subsoil is too dense to permit efficient leaching, the content of soluble salts of the soil may be markedly increased by applying saline irrigation water. Or if the amount of irrigation water that is actually applied per irrigation is light and the rainfall is insufficient to produce efficient leaching of the root zone, the salts contained in the irrigation water may accumulate in the soil to such extent as to produce serious injury. On the other hand, heavy precipitation tends to leach out the soluble salts that have accumulated in consequence of the use of saline irrigation water.

This brief discussion on the formation of alkali soil is given here primarily for the purpose of emphasizing the importance of drainage. Since poor drainage is the one condition which contributes most to the development of alkali in the soil, the first step to be taken in the reclamation of an alkali soil is the establishment of good drainage conditions. The importance of favorable drainage conditions can scarcely be overemphasized because water is the only agent by which soluble salts can be removed from the soil in a practical way, and good drainage is an essential condition for the effective removal of soluble salts by means of water.

From time immemorial many farmers of dry regions have been compelled to deal with alkali soils. Hilgard[3] spent a large part of his life investigating alkali soils. He showed quite clearly that the unproductivity of alkali soils is caused by the accumulation of excessive amounts of soluble salts; that different kinds of salts produce different degrees of injury to vegetation; and that, where the salts have accumulated excessively in the soil, their removal is essential to successful crop production.

Despite the importance of Hilgard's work[5] and the brilliance of his

[5] Hilgard's great book on soils[3] was based largely on investigations originally published in a series of Bulletins and Annual Reports of the California Agricultural Experiment Station from 1877 to 1904.

ideas, investigation in recent years has established the fact that an additional factor, not recognized by him, also plays an important part in many alkali soils. The reference here is to the chemical reactions and physical effects that are produced in the soil by soluble salts. Sodium salts may react chemically with the clay and humus of the soil and produce a condition which in itself is harmful to crops and which must be overcome before the soil can be said to be truly reclaimed. As a result of reactions between soluble sodium salts and the soil, sodium becomes absorbed. Sodium thus held by the soil is commonly referred to as absorbed sodium; consequently the content of absorbed sodium is determined by the extent to which soluble sodium salts have reacted with the clay and humus of the soil. Under extreme conditions, these chemical transformations of the clay and humus proceed so far as to render the soil highly toxic to ordinary crops and also to produce extremely bad physical conditions in the soil. Furthermore, these adverse conditions may persist after all the soluble salts have been removed by leaching. This is true because absorbed sodium is not readily removed by leaching. Under such conditions some special treatment may be necessary in addition to the removal of the soluble salts.

However, counteracting forces are often present. For example, if the soluble salts which accumulate in the soil or are applied as constituents of the irrigation water are composed in considerable part of calcium compounds, the adverse chemical and physical effects just alluded to fail to materialize to any great extent. Under such conditions soluble salts do not produce excessive chemical changes in the clay and humus of the soil. Where this is the case, mere drainage and leaching will suffice to produce complete reclamation of the soil. An example of this type of soil condition is found in the Imperial Valley. As Thomas[14] has shown, the excessively saline soils of certain parts of the Imperial Valley can be reclaimed readily and be caused to produce large yields of crops by the simple expedient of drainage and leaching without applying any chemical treatment whatever. These soils contain relatively large quantities of soluble calcium salts as well as large amounts of sodium salts.

As is well known, Hilgard conducted numerous experiments on the reclamation of alkali soils. During the past seventeen years the writer and his associates have also conducted extensive investigations on the reclamation of different types of alkali soils.[5, 6, 8, 14, 15] The results have shown that probably most of the important areas of alkali soil in California can be reclaimed successfully provided satisfactory drainage conditions can be established and an adequate supply of irrigation water is available. Simultaneous with these investigations in California have been

those of soil scientists investigating the alkali soils of other western states[1, 4, 9-12, 16] and of foreign countries. The result is that we now have a fairly complete understanding of the dominant principles of alkali soils, and reasonably satisfactory methods of reclaiming these alkali areas are available. The purpose of this bulletin is to make available

Fig. 1.—General conditions of the soil before the experiments were begun. Barley sown the previous fall failed to germinate over the greater part of this area. Photographed May, 1920. (From Bul. 455.)

to farmers the practical information that has resulted from these investigations.

In 1928 Kelley and Thomas[8] published the results of a series of reclamation experiments on the black-alkali soil of the Kearney Vineyard near Fresno. It was shown that the application of several different kinds of materials, such as sulfur, gypsum, and iron sulfate, gave good results with this soil. In view of the fact that the bulletin published in 1928 is now out of print, it seems desirable to repeat the essential features of that publication. More recently, we have completed some additional experiments, the results of which show that the reclamation of the Fresno soil can be accomplished at considerably less cost than was thought to be possible in 1928. These latter experiments will be discussed in this bulletin. In 1936 Thomas[14] discussed the results of reclamation experiments on white-alkali soil in the Imperial Valley, and a brief resumé of these results will likewise be given. Several experiments have also been made in other localities in California in coöperation with the county farm advisors, and reference will be made to this.

THE RECLAMATION OF BLACK-ALKALI SOILS

Experiments with Gypsum.—In the summer of 1920 a gypsum experiment was begun on an area of black-alkali soil near Fresno. The soil of this area is a sandy loam, classified as Fresno fine sandy loam, and when the experiments were begun, the soil contained considerable quantities of soluble salts, consisting chiefly of sodium chloride, sodium sulfate, and sodium carbonate. In addition the soil also contained significant amounts of absorbed sodium. A large part of the area used for experiment was so severely injured with alkali as to be highly toxic to crops (fig. 1). To certain plots gypsum was applied at the rate of 9 tons per acre, while certain plots were left untreated as checks. After plowing, all of the plots, including the untreated check plots, were flooded for a period of several weeks for the purpose of leaching out the soluble salts and of carrying the gypsum down into the subsoil. Barley was planted the following December. The results showed that gypsum produced considerable effect on the soil but the yields were unsatisfactory. Tests on the soil showed that it still contained a considerable amount of sodium carbonate. Consequently, an additional 6 tons per acre of gypsum was applied in the summer of 1921. Subsequently, no further material has been applied to these plots. They have merely been cultivated, irrigated, and cropped, as indicated in the tabular statement of the results.

TABLE 1

EFFECT OF GYPSUM ON BLACK-ALKALI SOIL
(Crop yields in pounds per acre)

Date	Crop	Plot 4; treated with gypsum	Plot 5; untreated
1920	Barley hay*	616	1,265
1921	Barley hay	2,671	1,567
1922	Barley hay	2,847	2,288
1923	*Melilotus indica* and cowpeas	Plowed under as green manure	Plowed under as green manure
1924	*Melilotus alba*		
1925	Alfalfa hay	5,272	3,174
1926	Uncropped	.....	.....
1927	Alfalfa hay	10,396	5,538
1928	Alfalfa hay	18,858	15,446
1929	Alfalfa hay	16,785	15,617
1930	Alfalfa hay	17,081	17,493
1931	Alfalfa hay	9,304	9,868
1932	Seed cotton	1,622	1,874
1933	Oat hay	3,084	3,163
1934	Alfalfa hay	12,671	13,622
1935	Alfalfa hay	19,101	18,878
1936	Alfalfa hay	14,691	14,698

* Data for 1920 represent yields produced immediately before the application of gypsum.

Table 1 gives the yields obtained from two representative plots of this experiment. To plot 4 a total of 15 tons per acre of gypsum was applied. Plot 5 was untreated. It will be noted that gypsum produced moderate increases in the yield of barley hay in 1921 and 1922, and large effects on the yield of alfalfa (fig. 2).

Fig. 2.—Alfalfa on plot 4 in 1930, ten years after gypsum was applied.

Fig. 3.—Alfalfa on untreated plot 5 in 1925, after leaching in 1920 and 1921. The plants in the foreground are chiefly *Tissa salina*, an alkali-resistant weed. Note that the alfalfa is practically a failure at this stage of the experiment. (From Hilgardia Vol. 8, No. 5.)

For several years after this experiment was begun, the untreated check plots produced unsatisfactory yields. During this period there were several spots of considerable size on these untreated plots where alfalfa and other crops failed completely (fig. 3). However, in 1928, eight years after the experiment was begun, the untreated check plots

Fig. 4.—Alfalfa on untreated plot 5 in 1930. The growth of alfalfa presented a striking contrast with that of 1925, shown in figure 3. (From Hilgardia Vol. 8, No. 5.)

began to show marked improvement in yields. Since that date the untreated checks have produced practically as well as the gypsum plots (compare figs. 2, 4, 5, and 6). Thus it is shown that the application of gypsum merely hastened the rate of reclamation of the soil but was not absolutely essential to the reclamation; in fact, as will be shown in a later section of this bulletin, it is possible to reclaim this soil relatively rapidly without applying gypsum or any other soil amendment.

The data show that the yields on both plots of this experiment declined markedly in 1931. The reduced yields of that year, as compared with those of previous years, were not caused by alkali, but rather by an invasion of Bermuda grass and a severe infestation of alfalfa wilt. A similar decrease in the yields of alfalfa took place on the plots of other experiments that will be reported in this bulletin (see tables 2, 3, 4, 6, 7, and 8). As the farmers of California are well aware, Bermuda grass commonly spreads into alfalfa plantings and thus crowds out the crop, sometimes at a rapid rate. For this reason the maintenance of a satisfactory

stand of alfalfa for a period of more than three to four years is often not possible.

Comparative Results with Sulfur and Gypsum.—The results of an experiment on the comparative effects of sulfur and gypsum as treatments for black-alkali soil are shown in table 2. The experiment was

Fig. 5.—Cotton on gypsum plot 4 in 1932.

Fig. 6.—Cotton on untreated plot 5 in 1932.

located adjacent to the previously discussed gypsum experiment on an area that was then almost completely barren of vegetation. Barley, sown the previous fall, had failed to germinate over a large part of these plots.

In May, 1921, 3,600 pounds per acre of finely ground uninoculated sulfur was applied to plot 10 and gypsum at the rate of 10 tons per acre to plot 11. These materials were plowed under at once, after which the soil was lightly irrigated and cultivated to promote the oxidation of sulfur. Since the oxidation of sulfur is a biological process which takes place gradually, considerable time must elapse before the effects will become evident. In the following September these plots were flooded twice for the purpose of leaching the materials down into the subsoil.

TABLE 2

COMPARATIVE EFFECT OF SULFUR AND GYPSUM ON BLACK-ALKALI SOIL

(Crop yields in pounds per acre)

Date	Crop	Plot 10; treated with sulfur	Plot 11; treated with gypsum
1921	Barley hay*	129	383
1922	Barley hay	268	1,619
1923	*Melilotus indica* and cowpeas	Plowed under as green manure	Plowed under as green manure
1924	Alfalfa hay†	4,000	1,500
1925	Alfalfa hay	16,515	11,492
1926	Alfalfa hay	21,158	12,853
1927	Alfalfa hay	18,347	13,509
1928	Barley hay	5,873	4,614
1929	Alfalfa hay	10,570	11,778
1930	Alfalfa hay	18,901	18,935
1931	Alfalfa hay	13,054	13,423

* Sulfur and gypsum were applied after the barley was harvested in 1921.

† Yields obtained from a single cutting in September.

Subsequently they have been cropped, irrigated, and cultivated as nearly alike as possible, but without applying any additional material to them.

Attention is called to the fact that in 1922, approximately one year after the materials were applied, gypsum had produced more marked effects than sulfur. The growth of cowpeas in the fall of 1922 and of *Melilotus indica* in 1923, gave the first definite evidence that the sulfur treatment was beginning to be effective. In 1924 the sulfur plot forged ahead of the gypsum plot, as indicated by the yield of alfalfa, and continued to give greater yields until 1928. However, after the second seeding to alfalfa in 1929 there has been no significant difference in the yields from these two plots. Both have produced well and the soil of both appears to be normal. Grapes, planted in 1932, have grown well on both plots and have shown no evidence of alkali injury.

Effect of Sulfur in Conjunction with Gypsum and Ground Limestone.—An experiment, begun in May, 1923, was designed to test the

effectiveness of sulfur when applied with gypsum and ground limestone. An inoculated form of sulfur was used at the rate of 2 tons per acre. The experiment consisted of five plots, four of which were treated with sulfur, the fifth being left untreated as a check. In addition to sulfur, gypsum was also applied to one plot at the rate of 2½ tons per acre and ground limestone to another plot at the rate of 2 tons per acre. After the applications were made in 1923 the soil was allowed to lie fallow until February, 1925, with only an occasional light irrigation and shallow

TABLE 3

Effect of Sulfur Applied in Conjunction with Gypsum and Ground Limestone to Black-Alkali Soil

(Crop yields in pounds per acre)

Date	Crop	Plot 21; treated with sulfur and gypsum	Plot 22; treated with sulfur and ground limestone	Plot 23; untreated	Plot 24; treated with sulfur alone
1925	*Melilotus alba*.....	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure
1926	Alfalfa hay.....	10,554	11,129	80	11,129
1927	Alfalfa hay.....	16,984	18,291	596	18,243
1928	Alfalfa hay.....	18,953	20,323	1,693	19,679
1929	Alfalfa hay.....	10,484	14,113	5,161	15,080
1930	Barley hay.....	5,000	6,450	2,095	5,565
1931	Alfalfa hay.....	12,661	15,242	9,596	14,233
1932	Alfalfa hay.....	14,033	15,161	14,516	18,106
1933	Alfalfa hay.....	12,422	16,814	16,885	18,549
1934	Alfalfa hay.....	12,097	16,289	17,823	18,385
1935	Oat hay.....	2,742	3,790	3,838	4,597
1936	Oat hay.....	6,129	5,645	6,613	6,853

cultivation. The plots were then flooded twice for the purpose of leaching, after which *Melilotus alba* was sown. The *Melilotus* was plowed under as a green manure in September, 1925. Alfalfa was sown in February, 1926. The seed germinated well on each of the sulfur plots but very poorly on the untreated check. The yields are reported in table 3.

Again it is shown that sulfur is remarkably effective with this soil. Practically the same yields of alfalfa were obtained from the sulfur treatment whether it was applied in conjunction with gypsum, or ground limestone, or without either of these materials. It is especially interesting to note that in 1926, 1927, and 1928, the effect of sulfur was very marked in comparison with the untreated check (figs. 7 and 8). For each of these three years the yield of alfalfa on the untreated check was extremely light, whereas the sulfur-treated plots gave high yields. However, the untreated check showed improvement each year after alfalfa

was first sown in 1926. By 1932 the yield on the untreated check had become practically equal to that of the sulfur plots, and since that date the growth of alfalfa and oats on the untreated check plot has fully equaled that of the sulfur plots; all of them have produced large yields (figs. 9, 10, and 11).

Thus it is shown, as in the case of the gypsum experiment already dis-

Fig. 7.—Failure of alfalfa on untreated plot 23 of the sulfur experiment. Photographed in 1926. (From Bul. 455.)

Fig. 8.—Alfalfa on sulfur plot 24 in 1926. (From Bul. 455.)

cussed, that this black-alkali soil can be gradually reclaimed without applying any soil amendment. However, the value of the increased yield produced by sulfur during the first three years of alfalfa culture greatly exceeded the cost of the sulfur and, therefore, the application was eco-

Fig. 9.—Alfalfa on untreated plot 23 in 1932. The appearance of the alfalfa on this plot was very different from that of 1926 (see fig. 7). No material other than irrigation water was applied to this plot.

Fig. 10.—Oats on untreated plot 23 in 1935.

nomically justified, notwithstanding the fact that reclamation can be effected without the application of sulfur. Further discussion on this point will be given in a later section of this bulletin.

Sulfur Applied to a Larger Area.—In the preceding experiments comparatively small plots were used (0.1 to 0.6 acre), the sulfur was applied at heavy rates (3,600 to 4,000 pounds per acre), and after several months the soil was flooded for a period of three or more weeks. It was decided to test sulfur on an area more nearly approaching practical

Fig. 11.—Oats on sulfur plot 24 in 1935.

farm conditions, to use sulfur at a lighter rate of application, and to omit the flooding entirely. Such an experiment was begun on a 7-acre area lying between the two previously reported sulfur experiments. The soil was spotted, but it embraced an area two to three acres in extent, which was entirely barren of vegetation at the outset and which contained large amounts of black alkali. This spot was as extreme in regard to alkali conditions as any part of the entire quarter section in which these experiments are located.

Finely ground uninoculated sulfur was applied in December, 1924, at the rate of approximately 1 ton per acre and disked in. *Melilotus alba* was sown in March, 1925. A fair crop resulted, which was plowed under as green manure in September, 1925. Barley, planted the following December, produced a satisfactory crop, but no record was made of the yield. In October, 1926, alfalfa was sown. The seed germinated well over

the entire area and a uniform stand was secured. The yields that have been obtained subsequently are recorded in table 4. These data show that the results have been highly satisfactory. In fact none of the crops (alfalfa, milo, and oats) that have been grown on this area since 1926 have shown any evidence of alkali injury.

Thus the amount of sulfur necessary for the reclamation of this soil is shown to be not greater than 1 ton per acre and it is not necessary to subject the soil to heavy flooding after sulfur has been applied. Since

TABLE 4

Effect of Sulfur on Black-Alkali Soil, Applied at the Rate of 1 Ton per Acre

(Crop yields in pounds per acre)

Date	Crop	Yields
1925	*Melilotus alba*	Plowed under as green manure
1926	Barley hay	Good crop—weights not recorded
1927	Alfalfa hay	12,913
1928	Alfalfa hay	18,404
1929	Alfalfa hay	15,886
1930	Alfalfa hay	14,565
1931	Alfalfa hay	9,492
1932	Milo (heads)	4,347
1933	Oat hay	3,060
1934	Alfalfa hay	12,776
1935	Alfalfa hay	18,299
1936	Alfalfa hay	13,225

the experiment was made on a comparatively large scale and since the effect of sulfur was uniformly good over the entire 7 acres, it is obvious that similar results should be obtained under ordinary farm conditions.

Effect of Sulfur Applied at the Rate of 1,000 Pounds per Acre.—A fourth sulfur experiment was begun in October, 1925, using only 1,000 pounds per acre. Two plots were treated, one of which had been treated in 1922 with ground limestone and the other with barnyard manure, but without any appreciable effect upon the crop-producing power of the soil. Uninoculated sulfur was used in this experiment and was plowed under in October, 1925. Alfalfa was sown the following February. The results are recorded in table 5.

As shown in the table, the effect of sulfur was much greater for the first few years of the experiment on plot 19 previously treated with manure than when applied where ground limestone had previously been used (plot 16). Later the yields became more nearly alike on these two

plots. It is probable that the manure produced some effect on the soil through the CO_2 and other organic acids that were produced by its decomposition, which, together with the microörganisms of the manure, favored the biological oxidation of sulfur. On the other hand, no evidence has been found that ground limestone produced any effect whatever, but this was expected for the reason that the soil already contained calcium carbonate.

TABLE 5

EFFECT OF SULFUR ON BLACK-ALKALI SOIL, APPLIED AT THE RATE OF 1,000 POUNDS PER ACRE.

(Crop yields in pounds per acre)

Date	Crop	Plot 16; treated with sulfur and ground limestone	Plot 19; treated with sulfur and manure	Plot 20; untreated
1924	Barley hay*	28	22	13
1925	*Melilotus alba*	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure
1926	Alfalfa hay	1,746	9,614	287
1927	Alfalfa hay	10,713	18,436	2,304
1928	Alfalfa hay	14,862	21,270	5,994
1929	Alfalfa hay	4,143†	14,365	5,525
1930	Barley hay	Uncropped	6,575	1,933
1931	Alfalfa hay	7,100	12,321	10,330
1932	Alfalfa hay	15,026	16,739	14,666
1933	Alfalfa hay	17,016	18,230	16,463
1934	Alfalfa hay	18,480	16,631	16,297
1935	Oat hay	2,929	4,310	4,310
1936	Oat hay	7,348	5,911	6,629

* Yields before sulfur was applied.
† Barley hay.

Practically as good results were produced by 1,000 pounds per acre as with the larger amounts used in the previous experiments. As in the experiments discussed earlier, the untreated check plots of this experiment gradually improved from 1926 to 1931, when the second seeding of alfalfa was made (figs. 12 and 13). Since that time the untreated check plots have produced approximately as well as the sulfur plots, and all of them have yielded satisfactorily. McGeorge and Greene[10] have also reported good results from sulfur applications in Arizona.

Comparative Effect of Inoculated and Uninoculated Sulfur.—An experiment was begun in July, 1927, for the purpose of comparing artificially inoculated sulfur with three forms of uninoculated sulfur of different degrees of fineness.[15] Eighty per cent of the inoculated sulfur that was used and also of the uninoculated elemental sulfur was less than 200 mesh in particle size; the coarse sulfur ranged from 16 to 70

Fig. 12.—Untreated plot 20 in 1926. The alfalfa was practically a failure at this time. (From Bul. 455.)

Fig. 13.—Alfalfa on untreated plot 20 in 1932. Note the marked improvement in this plot since 1926. (Compare with fig. 12.)

mesh. The size of the particles of the colloidal sulfur did not exceed 25 microns in diameter, which is approximately 1,000 mesh. The sulfurs were applied in July, 1927, at the rate of 1 ton per acre. Hubam clover was grown on these plots in 1928 and was plowed down as green manure in September, 1928. Alfalfa was sown in February, 1929. The results are reported in table 6.

These data show that there is no significant difference in the effectiveness of the different kinds of sulfur used in this experiment. Thus, the uninoculated sulfur produced as good results as the inoculated form, and coarse sulfur was practically as effective as the colloidal form. McGeorge and Greene[10] have also found that extreme fineness of subdivision of sulfur is not necessary. Again, it was found that the untreated check plots, although decidedly inferior to the sulfur plots for

TABLE 6

COMPARATIVE EFFECT OF INOCULATED AND UNINOCULATED SULFUR APPLIED TO BLACK-ALKALI SOIL

(Crop yields in pounds per acre)

Date	Crop	Inoculated sulfur	Uninoculated elemental sulfur	Uninoculated coarse sulfur	Uninoculated colloidal sulfur	Untreated plot
1928	Hubam clover.....	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure
1929	Alfalfa hay.....	10,937	10,000	10,058	10,097	4,082
1930	Alfalfa hay.....	19,344	19,475	20,998	21,446	10,606
1931	Alfalfa hay.....	17,225	16,865	20,497	21,024	14,774
1932	Alfalfa hay.....	7,363	7,598	8,887	8,945	5,918
1933	Oat hay.....	5,195	5,235	5,478	5,488	4,179
1934	Alfalfa hay.....	10,908	9,238	10,715	10,439	9,091
1935	Alfalfa hay.....	19,735	18,897	20,965	20,566	18,626
1936	Alfalfa hay.....	12,744	11,728	14,648	14,183	13,467

the first few years of the experiment, gradually improved in crop-producing power. For each of the last three years of this record the untreated checks have produced large yields of alfalfa, which have been practically equal to those obtained from the sulfur-treated plots.

Experiments with Iron Sulfate and Alum.—In August, 1922, an experiment was begun using iron sulfate at the rate of 9 tons per acre, and alum at the rate of 11 tons per acre. Immediately after these materials were applied, the plots were heavily flooded in order to leach out the soluble salts and to wash the applied material down into the subsoil. Barley was sown the following December and again one year later. The yields of barley were light. The appearance of the growing barley indicated nitrogen starvation. Accordingly, a leguminous covercrop was grown in 1925, followed by alfalfa. By reference to table 7, it will be seen that large yields of alfalfa, barley, and oat hay have been obtained. Knight[9] also secured good results in Nevada by applying a crude alum from a near-by deposit.

The untreated check plot of this experiment showed a trend similar to that of the check plots of the previously described experiments, the

yields being extremely light for several years and then heavy for several years.

Another iron sulfate experiment was begun on plot 45 in October, 1925, the material being applied at the rate of 5 tons per acre. After one flooding this plot was seeded to alfalfa in February, 1926. The yields obtained have been remarkably heavy, as shown in table 7.

The use of iron sulfate probably affords one of the most rapid methods of reclaiming this soil, but the cost is too high for general reclamation

TABLE 7

Comparative Effect of Iron Sulfate and Alum Applied to Black-Alkali Soil

(Crop yields in pounds per acre)

Date	Crop	Plot 14; untreated	Plot 17; treated with iron sulfate	Plot 18; treated with alum	Plot 45; treated with iron sulfate
1923	Barley hay	486	2,215	935	.....
1924	Barley hay	177	1,014	737	.....
1925	Hubam clover	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure	Plowed under as green manure
1926	Alfalfa hay	133	10,939	9,503	12,795
1927	Alfalfa hay	569	17,657	17,277	20,592
1928	Alfalfa hay	470	23,203	20,939	20,087
1929	Alfalfa hay	2,265*	15,468	15,635	13,100
1930	Barley hay	Uncropped	5,525	4,530	6,330
1931	Alfalfa hay	5,634	13,590	12,762	13,099
1932	Alfalfa hay	9,998	14,583	15,910	14,325
1933	Alfalfa hay	13,009	16,905	18,093	15,325
1934	Alfalfa hay	14,226	14,307	16,432	14,104
1935	Oat hay	1,657	4,198	3,978	5,500
1936	Oat hay	5,691	5,746	6,519	8,209

* Barley hay.

purposes. As a means of quickly reclaiming isolated small spots in areas surrounded by good soil, iron sulfate might possibly be utilized to advantage.

Reclamation without Soil Amendment.—In view of the fact that the untreated check plots of each of the foregoing experiments gradually improved in crop-producing power and finally came to yield fully as well as where gypsum, sulfur, iron sulfate, or alum was applied, a special investigation was begun in 1930 for the purpose of exploring this point further. As practical farmers are well aware, Bermuda grass commonly invades alfalfa plantings throughout the San Joaquin Valley and in other of the warm parts of California and other southern states. The result is that after a few years Bermuda grass usually crowds out alfalfa to such extent as to necessitate plowing the land and reseeding. Usually some other crop is grown for a few years for the purpose of eradicating

this grass. As is also well established, Bermuda grass will tolerate large amounts of alkali. In fact, it is able to grow fairly well in strongly alkaline soil. The plots of the previously mentioned experiments are no exception to this rule. Throughout the course of this investigation we have been compelled to plow up alfalfa some three to five years from the time of seeding on account of Bermuda-grass infestation and to devote much effort to the eradication of the latter. Each of the untreated check plots in these experiments gradually became covered with it. There seemed to

TABLE 8

EFFECT ON PRODUCTIVITY OF BLACK-ALKALI SOIL FROM GROWING BERMUDA GRASS FOR TWO YEARS

(Crop yields in pounds per acre)

Date	Crop	Yields	Date	Crop	Yields
1932	Barley hay	2,495	1935	Alfalfa hay	17,163
1933	Alfalfa hay	10,872	1936	Alfalfa hay	10,650
1934	Alfalfa hay	20,805	1937	Oat hay	3,465

be a possibility that the growth of Bermuda grass was itself responsible for the gradual reclamation of these untreated check plots.

Accordingly, a special experiment was begun to test this possibility. A series of plots embracing an area badly affected with black alkali were laid out in February, 1930, the purpose being to encourage the growth of Bermuda grass. These plots were irrigated approximately once each three weeks throughout the warm months of 1930 and 1931. Bermuda grass, already established on the area, made vigorous growth during this time. In the fall of 1931 the plots were plowed and seeded to barley. After the barley was harvested in May, 1932, the plots were plowed at once and then allowed to remain fallow without irrigation until the following winter. During the fallow period the plots were harrowed occasionally for the purpose of eradicating the Bermuda grass. Alfalfa was sown in February, 1933. The results are shown in table 8.

Large yields have been obtained from this area. In fact the results have been fully as satisfactory as in other experiments where sulfur or gypsum was applied. The diminished yield in 1936, as compared with that of previous years, was not due to alkali but to the encroachment of Bermuda grass coupled with an infestation of alfalfa wilt. All but a small spot, located in the worst part of this area, has already been completely reclaimed. The area as a whole has produced large yields of alfalfa for four years and satisfactory yields of grain the other two years of the experiment.

Thus it is shown that the type of black-alkali soil prevailing in the Fresno area can be reclaimed by intensive irrigation with the soil covered with Bermuda grass. In view of the fact that Bermuda grass affords valuable pasturage for dairy cattle and other farm animals in this locality, a large part of the cost entailed in its irrigation can be met by the returns obtained from pasturing. Consequently, the cost of reclamation by this method was very moderate indeed. The total cost of all operations during the six years of this experiment has been considerably less than the value of the harvested crops; in fact this has proved to be the most economical method of reclamation yet found. Chemical investigations of the soil from this plot, which are presented in a later section of this bulletin (table 14), also show that the reclamation has been highly satisfactory.

This method rests on the same principles and involves some of the technique employed in the irrigated-meadow experiment at Békéscsaba, Hungary.[13] In the Hungarian experiment a mixture of several different grasses and legumes has been grown successfully on a heavy black-alkali soil, and at the same time the soil has undergone gradual amelioration. Knight[9] has successfully employed a somewhat similar method at Fallon, Nevada, as have Powers and his associates[4, 16] at Vale, Oregon. Since, as is well known, CO_2 is given off by the roots of all plants, it is probable that the chemical reactions resulting from it are responsible for the reclamation. The irrigation water not only washes the CO_2 down into the alkali zone where it can take effect, but also leaches the transformed salts out of the soil.

Coöperative Experiments.—In addition to the previously discussed experiments, practical trials have also been made on black-alkali soil in Kern, Tulare, Los Angeles, and Kings counties in coöperation with the farm advisors in those counties. All these trials, except that of Kings County, have yielded satisfactory results. In the Kern County experiments on the A. S. Harper Ranch, known as La Kern Farms Co. No. 1, near Bakersfield, both sulfur and gypsum were applied to separate plots. After the lapse of a few years the treated plots produced good yields of alfalfa. Similar results were obtained on the farm of P. M. Longan in Tulare County and also on the Los Angeles County Farm. On the other hand, the results obtained on the W. G. Clark farm in Kings County have not been satisfactory. In this last-named case, the soil contained exceptionally large amounts of soluble carbonate and absorbed sodium. Moreover, the subsoil was heavily charged with black alkali. As shown in table 15, a considerable part of the soluble carbonate and absorbed sodium originally present in the soil has been leached down into the sub-

soil by the treatments, but not sufficiently to permit satisfactory growth of alfalfa. An additional application of sulfur has recently been made, but further time must elapse before the effects will become manifest. In pot experiments conducted by Thomas at Riverside with soil from the Clark Ranch good results were obtained with both gypsum and sulfur, but the rates of application were much greater than in the field experiments. It is possible that a few years' growth of some alkali-resistant plant, such as Bermuda grass or *Melilotus alba,* combined with a moderate application of gypsum or sulfur, may be a successful method of reclaiming this soil.

This experience with the Kings County soil illustrates a very important practical point, namely, that heavy types of black-alkali soil, or any type that contains exceptionally large amounts of soluble carbonate and absorbed sodium is much more difficult to reclaim than light types of soil, and may require such large applications of gypsum or sulfur as to render reclamation too expensive for economic success. It remains to be determined whether some other method can be found that will give satisfactory results with this particular soil. Fortunately, heavy types of soil comprise only a small percentage of the black-alkali soil area of California.

Experiments at Vale, Oregon.—The Oregon Agricultural College has investigated black-alkali soil at Vale, Oregon, for many years.[4, 16] The results have agreed well with those obtained in California. The application of either gypsum or sulfur proved to be effective with this soil but, just as was found in California, sulfur proved to be the more efficacious. In these Oregon experiments, seeding with a mixture of rye grass, bluegrass, *Melilotus alba,* and alsike clover, followed by liberal irrigation, materially aided in the reclamation. Apparently, at least some of these plants have a high alkali tolerance, somewhat like that of Bermuda grass which grows in warmer sections. The Vale soil is somewhat heavier and contains much larger amounts of both soluble carbonate and absorbed sodium than the Fresno soil. Therefore it is more difficult to reclaim than the Fresno soil.

Experiments at Fallon, Nevada.—The United States Department of Agriculture has conducted extensive alkali-reclamation experiments on an area near Fallon, Nevada.[9, 11, 12] The original soil contained excessive amounts of soluble salts and probably absorbed sodium also. Knight[9] concluded, on the basis of many years' experience, that the first step to be taken in the reclamation of this soil was the establishment of an adequate drainage system. After the water table had been lowered, the application of gypsum, alum, sulfuric acid, or sulfur, coupled with heavy

leaching, gave good results on the more porous types of this soil, but the cost was relatively high owing to the large amounts of these materials that were required.

On an area where the soil was comparatively heavy and the subsoil was adobelike in character, Knight reported that the following method gave good results: First, each irrigation check was carefully leveled; second, 20 or more tons of manure per acre were applied and disked in to a depth of 2 or 3 inches only. At this stage the soil was not plowed, the immediate object being to ameliorate the surface soil so as to make possible the growth of shallow-rooted grasses and legumes. After disking in the manure, the plots were releveled, if necessary, and then irrigated every two weeks for several months. Each irrigation was followed by shallow cultivation. During this time no crop was grown. After about one year, manure was applied a second time and disked in, but plowing was again omitted. If necessary, each check was again releveled.

The first crop planted was sweet clover or some other crop that permits frequent and comparatively heavy irrigation and which is relatively tolerant of alkali. The resulting growth was left on the land and disked in the following spring. Alfalfa or some pasture grasses were then sown but the soil was not plowed at this stage owing to the danger of bringing to the surface toxic alkali soil.

By following this method carefully, Knight found that the subsoil was gradually ameliorated. After a few years in grass or alfalfa, the soil could be plowed in the usual way. The essential features of the method, as reported by Knight, closely paralleled those used in certain parts of Hungary, as discussed by de 'Sigmond.[13] This method of reclamation is obviously based on the use of farm manure and farm labor without the necessity of purchasing materials for treatment, and is directed towards the gradual amelioration of the soil from the surface downward. It is doubtful whether this method can be applied economically in California without substantial modification owing to the relatively high sales value of farm manure in California and the cost of the required labor. However, the fundamental principles involved are essentially the same as in the Bermuda-grass experiment referred to previously.

THE RECLAMATION OF WHITE-ALKALI SOIL

Experiments in the Imperial Valley.—Experiments[14] were begun in May, 1929, on an area of barren white-alkali soil of the Holtville silty clay series near El Centro. The soil contained large amounts of neutral soluble salts consisting chiefly of chlorides and sulfates of sodium, calcium, and magnesium, but no important amount of black alkali. The

Fig. 14.—Condition of the Imperial Valley soil before the experiment was begun. Photographed in 1929. (From Hilgardia Vol. 8, No. 5.)

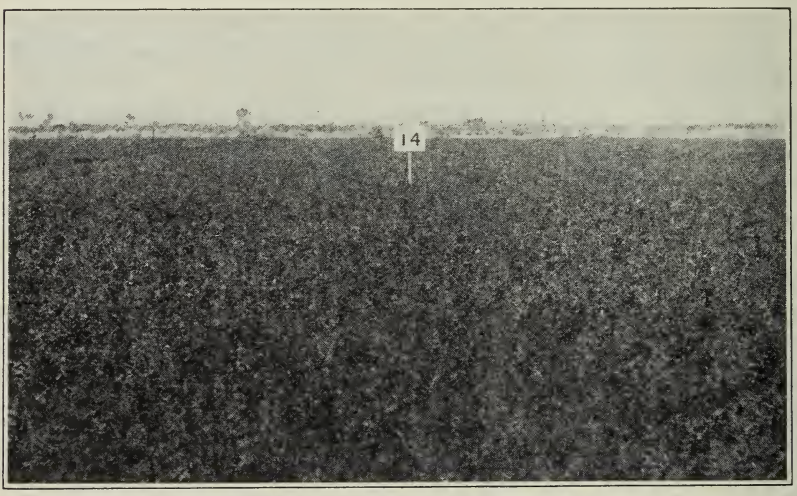

Fig. 15.—Alfalfa on a plot that was leached in 1929 and 1930. Photographed in 1931. (Compare with fig. 14.)

experiment embraced 10 one-half acre plots, 3 of which were left untreated as controls and 7 of which were treated with gypsum, sulfur, or manure, either singly or in various combinations (table 9). After these materials were applied, all of the plots, including the untreated checks, were plowed and seeded to sesbania, a plant that is relatively alkali-tolerant. The germination and growth of the sesbania was extremely

spotted owing to the sporadic distribution of the soluble salts in this soil. After the sesbania was plowed under as a green manure the latter part of August, 1929, all of the plots were flooded for three successive periods of several weeks each, for the purpose of leaching out the soluble salts. After the flooding periods, which extended from November 16, 1929, to May 10, 1930, the plots were plowed and seeded to guar, another alkali-tolerant plant. The guar crop was plowed under the latter part of August, 1930, and the plots were seeded to alfalfa on October 15, 1930. A

TABLE 9

Results of Reclamation Experiment on White-Alkali Soil in the Imperial Valley

(Crop yields in pounds per acre)

Plot	Treatment, and rate of application per acre	1931	1932	1933	Three-year total
10	Gypsum, 1½ tons	10,342	10,240	8,620	29,202
11	Untreated	10,434	11,110	8,400	29,944
12	Manure, 10 tons	13,098	13,380	9,920	36,398
13	Sulfur, 500 pounds	10,906	12,960	9,820	33,686
14	Untreated	10,040	12,430	10,120	32,590
15	Sulfur, 500 pounds Gypsum, 1½ tons	11,742	13,774	10,780	36,296
16	Manure, 10 tons Gypsum, 1½ tons	13,146	15,570	10,500	39,216
17	Untreated	13,178	14,030	9,740	36,948
18	Manure, 10 tons Sulfur, 500 pounds	11,678	12,100	8,280	32,058
	Average	11,618	12,844	9,575	34,037

uniformly good stand was secured on all the plots, including the untreated check plots (figs. 14 and 15).

Table 9 gives the treatments and yields of alfalfa hay that were obtained for each of three successive years. All of the plots yielded well, no important difference being found between the untreated and the treated plots. When account is taken of the fact that a severe infestation of alfalfa caterpillar reduced the yields on certain plots more than others, it is certain that neither gypsum nor sulfur nor manure produced any important effect. The attack of the alfalfa caterpillar reduced the yield to a considerable extent on all of the plots in 1933. This fact, together with the insufficiency of the irrigation supply during the latter part of that year, was responsible for the decline in yields as compared with 1932.

The net conclusion to be drawn from this experiment is that the reclamation of this soil is merely a matter of drainage and leaching and that treatment with such materials as gypsum, sulfur, or manure, is entirely

unnecessary. In the event that alfalfa is the first harvestable crop grown, it is doubtful whether anything of value will be gained by growing a green-manure crop such as sesbania or guar on soil of this type. This, of course, is not intended to mean that there is no value in covercropping as such, but rather that alfalfa can be grown successfully after the soluble salts have been leached out without the use of a covercrop.

In view of the fact that the composition of the soluble salts originally present in this soil was similar to that found in many thousands of acres of alkali soil in the Imperial Valley, it is believed that similar results can be obtained in other portions of the Imperial Valley wherever the ground water can be lowered sufficiently and where the soil is sufficiently porous to permit drainage and leaching. However, it is doubtful whether it is economically feasible to drain and leach those areas of the Imperial Valley that are characterized by heavy clay subsoil of great depth, as are many of the soils classified in the Imperial and Meloland series. On the other hand, soils belonging to the Holtville and Rositas series are characterized by a sandy stratum in the subsoil and can be drained effectively. Drainage is undoubtedly the most important consideration in the reclamation of the saline types of alkali soil occurring in the Imperial Valley.

Experiment at Oxnard.—In collaboration with the Farm Advisor of Ventura County, an alkali-reclamation experiment has been in progress for several years on an area near Oxnard. The soil is a comparatively heavy type and originally contained large amounts of white alkali. The results have shown that drainage and leaching gradually removed the excess of soluble salts and permitted the satisfactory growth of alfalfa and sugar beets.

Experiment in the Yuma Valley, Arizona.—In 1928, Burgess[1] reported the result of an alkali-reclamation experiment on a heavy type of white-alkali soil in the Yuma Valley of Arizona. Large amounts of soluble salts were distributed throughout the profile of this soil. The experiment was carried out on several plots, some of which were treated with manure, others with soluble calcium salts, and still others were left untreated. All of the plots were heavily leached for a considerable period. Burgess reported that a uniformly good stand of alfalfa was obtained about two years after the plots were flooded and that the growth of alfalfa was practically as good on the untreated checks as where manure or calcium salts had been applied. The subsequent yields obtained from all the plots were satisfactory. Analysis showed that the soluble salts were effectively removed from the soil by the leaching process, being somewhat more effectively removed where calcium salts were applied.

The outcome of this experiment agreed well with the results obtained by Thomas in the Imperial Valley of California. It is probable that the Yuma soil is heavier than that used in the Imperial Valley. In fact, Burgess considers the Yuma soil one of the most difficult to reclaim.

Summary of Results in Reclaiming White-Alkali Soils.—In view of the fact that drainage and leaching have produced satisfactory results with white-alkali soils in the Imperial Valley and Oxnard sections of California, in the Yuma Valley of Arizona, and also in several localities in Utah and Colorado, it seems safe to conclude that any white-alkali soil can be reclaimed by simple leaching, provided good drainage can be established. Obviously, the readiness with which the reclamation can be accomplished will depend on the efficiency of the drainage system and the ease of leaching out the soluble salts. With heavy types of soil, especially those overlying dense, heavy clay subsoils, reclamation is sure to be relatively difficult.

Good drainage conditions mean the total absence of free water in the soil to a depth well below that of root penetration, and not merely the establishment of a series of drains in a given area. In certain localities where the subsoil is very heavy it has been found that the level of free water was effectively lowered by drains only in the soil adjacent to the established drains. At a distance of 40 to 50 feet from the drains the water level was not lowered perceptibly. In such cases the soil was not effectively drained.

The safe minimum depth to ground water may vary somewhat in different localities, with such factors as the sensitivity of the crops that are grown, the rooting habit of the crops, the abundance of the irrigation supply, and the length of the annual irrigation season. Preferably the ground water should never be less than 8 to 10 feet below the surface and every reasonable effort should be made to prevent its rising nearer than 5 to 6 feet from the surface, even for brief periods.

CHEMICAL EFFECTS OF TREATMENTS

Fresno Type of Black Alkali.—Samples of soil were drawn from the previously discussed experimental plots both before the experiments were begun and again several years later. Analysis has shown (tables 10–14) that practically all of the soluble salts and the greater part of the absorbed sodium have been removed from the Fresno soil by each method that has been tried. It is also worthy of note that the soluble calcium content of the soil was increased by applying both gypsum and sulfur, and that the same general type of chemical change has taken place in the untreated check plots and in the Bermuda grass plots as in

TABLE 10

CHEMICAL ANALYSIS, FRESNO BLACK-ALKALI SOIL, PLOT 4, TREATED WITH GYPSUM

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before treatment (1920)								
0–12	0.94	0.32	0.20	Trace	2.06	1.08	3.13	70
12–24	0.49	0.46	0.21	Trace	1.47	0.42	2.87	67
24–36	0.43	0.39	0.14	Trace	1.09	1.78	2.41	54
36–48	0.15	0.32	0.13	Trace	0.82	2.57	1.59	35
After treatment (1931)								
0–12	0.00	0.05	0.02	0.23	0.24	5.05	0.27	5
12–24	0.00	0.08	0.04	0.17	0.27	4.53	0.40	8
24–36	0.15	0.08	0.04	0.12	0.50	4.63	0.43	8
36–48	0.15	0.10	0.04	0.07	0.67	4.13	1.00	19

TABLE 11

CHEMICAL ANALYSIS, FRESNO BLACK-ALKALI SOIL, PLOT 10, TREATED WITH SULFUR

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before treatment (1921)								
0–12	1.15	1.53	0.65	Trace	4.06	1.35	2.51	58
12–24	0.60	1.24	0.41	Trace	2.72	1.21	2.90	65
24–36	0.53	0.70	0.19	Trace	1.90	3.19	2.00	37
36–48	0.42	0.50	0.12	Trace	1.41	3.61	1.26	25
After treatment (1931)								
0–12	0.00	0.05	0.04	0.10	0.24	4.06	0.21	5
12–24	0.00	0.05	0.05	0.12	0.28	3.75	0.44	10
24–36	Trace	0.07	0.07	0.07	0.57	4.05	0.38	8
36–48	0.30	0.07	0.10	Trace	0.79	3.66	0.85	17

TABLE 12

Chemical Analysis, Fresno Black-Alkali Soil, Untreated Check Plot 14

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before leaching (1922)								
0–12	0.60	1.43	0.65	Trace	3.41	0.93	2.94	60
12–24	0.40	0.80	0.18	Trace	1.87	2.71	1.78	36
24–36	0.20	0.80	0.33	Trace	1.84	3.18	1.62	31
36–48	0.10	1.13	0.37	Trace	2.08	3.59	1.28	24
After leaching (1936)								
0–12	0.00	0.17	0.07	Trace	0.62	3.94	0.00	0
12–24	0.05	0.17	0.05	Trace	0.66	2.94	1.28	27
24–36	0.35	0.25	0.07	Trace	1.01	3.91	1.04	19
36–48	0.40	0.22	0.03	Trace	0.95	3.61	1.35	25

TABLE 13

Chemical Analysis, Fresno Black-Alkali Soil, Untreated Check Plot 23

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before leaching (1923)								
0–12	0.60	3.13	1.37	Trace	5.63	0.00	3.42	80
12–24	0.50	1.65	0.55	Trace	3.12	1.14	2.31	55
24–36	0.20	0.70	0.19	Trace	1.51	2.76	1.14	28
36–48	0.10	0.75	0.28	Trace	1.47	3.62	0.76	16
After leaching (1936)								
0–12	0.00	0.07	0.05	0.12	0.21	3.31	0.39	9
12–24	0.02	0.07	0.03	Trace	0.51	3.53	0.37	9
24–36	0.17	0.07	0.02	Trace	0.59	2.89	1.04	25
36–48	0.50	0.12	0.03	Trace	1.17	3.51	1.06	22

the gypsum or sulfur plots. In the case of the untreated check plots, however, the absorbed sodium has not been as completely removed from the subsoil as in the gypsum and sulfur plots. Continued irrigation and cropping of the check plots probably will gradually reduce the content of absorbed sodium and ultimately remove it completely from the entire root zone. Therefore, the chemical analyses confirm the crop records. In a word, they show that the reclamation, whether it was effected by treatment with gypsum or sulfur or by leaching accompanied by the growth

TABLE 14

CHEMICAL ANALYSIS, FRESNO BLACK-ALKALI SOIL, BERMUDA-GRASS PLOT 80

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before leaching (1930)								
0–12	1.00	0.18	0.07	Trace	1.66	1.27	2.44	57
12–24	1.50	0.98	0.33	Trace	3.19	0.00	4.47	97
24–36	1.55	1.93	0.77	Trace	4.32	0.33	4.60	90
36–48	0.75	1.35	0.36	Trace	2.74	2.70	2.29	43
After leaching (1937)								
0–12	0.00	0.28	Trace	Trace	0.61	3.99	0.05	1
12–24	0.00	0.18	Trace	Trace	0.58	3.97	0.19	4
24–36	0.20	0.23	Trace	Trace	0.76	3.85	0.69	13
36–48	0.35	0.38	Trace	Trace	1.11	4.69	0.20	4

of Bermuda grass, has produced practically complete reclamation of this soil.

Kings County Black-Alkali Soil.—Analysis of soil samples drawn from one of the experimental plots on the W. G. Clark Ranch of Kings County is reported in table 15. The results show that a considerable part of the soluble salts and absorbed sodium has been leached down into the subsoil, but the effects have not gone far enough to permit good crop growth. Therefore, the failure of alfalfa on these plots was obviously due to the toxic alkali conditions which, despite the treatment with sulfur or gypsum, still existed in this soil. This experiment is being continued.

Imperial Valley White-Alkali Soil.—Analysis of soil samples from one of the untreated check plots of the Imperial Valley experiment is reported in table 16. Here it is shown that this soil originally contained extremely large amounts of soluble salts, but only small amounts of

TABLE 15

Chemical Analysis, Hanford Black-Alkali Soil, Sulfur Plot 4

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	CO_3	Cl	SO_4	Ca	Na	Ca and Mg	Na	
Before treatment with sulfur (1926)								
0–12	3.80	1.00	0.48	Trace	5.48	0.00	17.75	95
12–24	2.55	0.40	0.03	Trace	3.85	2.54	13.19	79
24–36	0.95	0.30	0.05	Trace	2.13	10.91	7.53	42
36–48	0.10	0.15	0.03	Trace	1.04	13.20	1.35	9
After treatment (1937)								
0–12	0.85	0.10	0.52	Trace	2.15	9.00	7.55	43
12–24	2.10	0.25	0.43	Trace	3.38	5.49	11.82	64
24–36	2.05	0.30	0.40	Trace	3.44	5.99	13.56	67
36–48	1.55	0.33	0.58	Trace	2.90	5.43	10.80	64

TABLE 16

Chemical Analysis, Imperial Valley White-Alkali Soil, Untreated Check Plot 14

Depth in inches	Water-soluble ions, in milliequivalents per 100 grams					Absorbed bases in milliequivalents per 100 grams		Na as per cent of total absorbed Ca, Mg, K, and Na
	Cl	SO_4	Ca	Mg	Na	Ca and Mg	Na	
Before leaching (1929)								
0–12	77.4	10.4	24.4	12.6	48.3	15.8	1.1	6
12–24	20.5	4.0	4.6	2.6	15.1	15.4	2.1	11
24–36	11.8	3.1	2.6	1.6	9.6	14.9	2.4	13
36–48	9.0	3.4	1.6	1.1	8.6	20.9	3.0	12
After leaching (1931)								
0–12	0.6	1.8	0.8	0.7	1.0	17.3	2.1	10
12–24	0.9	2.4	0.5	0.4	2.6	16.8	1.6	8
24–36	1.2	1.9	0.2	0.5	2.6	16.4	1.2	7
36–48	1.2	3.7	0.1	0.4	2.7	21.0	2.0	8

absorbed sodium. Leaching removed the soluble salts remarkably effectively to a depth of at least 4 feet. Similar results were obtained in the Oxnard experiment, although the rate of salt removal was not so rapid as in the Imperial Valley.

THE PHYSICAL CONDITION OF THE SOIL

It is well known that black-alkali soils are characterized by extremely poor physical condition. Upon drying after rains or irrigation, the soil bakes to a condition of extreme hardness. When plowed, it breaks into harsh clods that are difficult to pulverize. To prepare a good seedbed in such soil is extremely difficult. Leaching generally aggravates this condition, sometimes to a pronounced degree. As long as a black-alkali soil contains considerable soluble salts the colloidal constituents tend to be flocculated, but when the soluble salts have been partially leached out, deflocculation sets in with the result that the permeability of the soil becomes so impaired as seriously to hinder the penetration of water. For this reason soil investigators usually advise against leaching as a practical method of reclaiming black-alkali soils.

The physical state of the Fresno soil was extremely adverse when our experiments were begun. The application of gypsum, iron sulfate, or alum, overcame this condition rapidly. After applying sufficient amounts of these materials and irrigating thoroughly, the physical character of the soil changed rapidly. It soon became granular and mellow. The same type of change took place after the application of sulfur but with this noteworthy difference, namely, that the physical structure of the soil improved much more gradually. Usually it was several months, and sometimes a year or more, before the adverse physical effects were overcome by treatment with sulfur. This was to be expected because sulfur produces practically no effect, either physical or chemical, until it has become oxidized; and oxidation of sulfur is a gradual process requiring a year or more for completion.

The physical condition of the soil of the untreated check plots of the Fresno experiments has not yet become quite so good as where gypsum or sulfur was applied. When plowed, the untreated checks tend to break into clods and to resist pulverization to a somewhat greater degree than the gypsum and sulfur plots. Nevertheless, they have produced satisfactory yields of crops for several years. Moreover, the tilth of the untreated plots has progressively improved for several years. The physical effects produced by growing Bermuda grass have been especially noticeable. In an experiment not reported herein, leaching in the absence of

plant growth has been compared with leaching in the presence of growing Bermuda grass. The difference produced on the physical character of the soil has been very striking. The plots on which the Bermuda grass was grown for one or two years became granular, whereas the bare plots remained badly deflocculated and broke up into a mass of hard clods.

The changes in the physical condition of the Fresno soil, produced by the various treatments referred to above, have become so great that strangers visiting the experiments for the first time frequently question whether this was ever a black-alkali soil. The tilth and soil structure have become profoundly changed. Whereas the plots originally absorbed irrigation water or rains extremely slowly, water now penetrates them freely, and their tilth has been greatly improved. The soil of these plots has become essentially normal in crop-producing power, chemical properties, and physical condition. Therefore, it is no longer to be regarded as an alkali soil.

Leaching a white-alkali soil also tends to cause more or less deflocculation owing to the removal of soluble salts, especially if the soluble salts are chiefly sodium compounds; but the effect of leaching white-alkali soils rarely becomes as extreme as with black-alkali soil. The difference in physical properties between these two classes of soils is largely due to the nature of the clay materials which they contain. Black-alkali soils always contain more or less absorbed sodium, while the white-alkali soils of the United States are more likely to contain a relatively large amount of absorbed calcium. The former type of clay becomes highly dispersed upon leaching, whereas the latter does so to a limited extent only. A few years' cropping with alfalfa, or the growing of green-manure crops on the white-alkali type, will usually so improve the physical conditions as effectively to produce normal flocculation of soil colloids. Root growth and organic matter when plowed under as a green manure are very potent in their effects on the porosity of the soil.

No attempt will be made in the present bulletin to give a theoretical discussion of the factors that are responsible for the physical properties of alkali soils; suffice it to say that various theories have been proposed but none of them is entirely satisfactory.

It is important for the practical farmer to realize that profound chemical, physical, and biological changes take place in soils in consequence of the accumulation of salts; these are likely to result in serious economic loss that can be rectified only by the operation of time or by relatively heavy expenditure. For these reasons the prevention of the spread of alkali is fundamentally much more important than reclamation.

IMPORTANCE OF GOOD FARMING METHODS

As was emphasized by de 'Sigmond,[13] Knight,[9] and Thomas,[14] practical success in the utilization of alkali soils is very largely dependent upon the application of the best possible methods of soil management. This is especially true in connection with alkali-soil reclamation. Chemical treatment may be a material aid in the reclamation of black-alkali soils, and, if excessive salts are present, leaching is an indispensable step in the reclamation of any alkali soil; nevertheless, neither chemical treatment nor leaching is a satisfactory substitute for good soil management. It is, of course, entirely possible to remove the soluble salts and the absorbed sodium by leaching and chemical treatment, but it is rare to find that a truly normal physical condition of the soil will be produced by these means alone. Moreover, the financial condition of the farmer of alkali soil usually compels him to attempt some sort of cropping well in advance of the removal of the last traces of the alkali condition from his soil. Since, in the early stages of cropping in connection with alkali reclamation measures, the soil will probably still contain more or less alkali, the germination of seeds and growth during the seedling stages of the crop are handicapped. The processes accompanying root growth and the decay of crop residues may be utilized as material aids in the reclamation process, but benefit can be derived from these processes only to the extent that the farmer is able to succeed in growing crops. For this reason good farming methods are extremely important.

Leveling.—The first point to be emphasized relates to the proper leveling of the land before leaching or cropping is undertaken and again whenever there is need for it. Usually it is necessary to relevel the soil after each plowing. The more perfectly level each irrigation check is prepared the better. Unless the checks are approximately level and kept so, uniformly effective leaching and irrigation are not possible because water, applied by the flooding system of irrigation, will not be uniformly distributed. Moreover, if irrigation water is allowed to stand in low places within a given check when the weather is hot, injury to tender crops such as young alfalfa is almost certain to result through scalding.

Moisture Conditions.—The moisture condition at the time of seeding is supremely important for two reasons: first, it is difficult to prepare a good seedbed on black-alkali soil unless the moisture conditions of the soil at the time of tillage closely approximate the optimum; secondly, it is possible to secure satisfactory germination of the seeded crop only when the soil is adequately moist. Should it be found necessary to irrigate after seeding in order to provide the moisture necessary for germi-

nation, the soil will run together and upon drying out will form a hard crust through which the young seedlings will often be unable to penetrate. However, it is by no means impossible to avoid the necessity of irrigation at this stage of cropping. In the experimental work reported herein involving scores of seedings to alfalfa, oats, and barley in the hot dry climate of the Fresno district, irrigation has never been found necessary in order to secure germination. This has been accomplished simply by seeding only when the soil moisture conditions were favorable. In the warm parts of California, alfalfa, barley, and oats should be sown in the fall or winter months when evaporation is at a minimum.

Frequence of Irrigation.—The frequence of irrigation is another factor of great practical importance. No set rules can be laid down concerning this point because of soil and climatic variation. At Fresno we have usually irrigated young alfalfa once every week or ten days until after the first cutting. After the first cutting we have gradually lengthened the irrigation interval to a maximum of about three weeks. As the crop becomes established, the amount of water applied per irrigation is also increased. The primary object should be to keep the soil moist. As the soil becomes dry, the concentration of soluble salts in the soil solution increases, and there is always danger of injury to the crop unless the soil is kept well above the wilting point. Moreover, water should be applied in excess of that required by the growing crop, in order that more or less leaching may take place. The soluble salts should be caused to move downward at each irrigation. By this means the alkali will finally be removed from the soil completely. During periods of hot weather water should be applied to young alfalfa only in the late afternoons. The following forenoons any water still standing on the surface of the soil should be drained off at once. The results of our experience at Fresno agree well with that of Knight[9] at Fallon, Nevada.

Careful attention to (1) leveling each and every irrigation check, (2) the moisture conditions of the soil at the time of seeding, and (3) the frequence of irrigation after the crop has germinated, will go far toward insuring success in alkali-land reclamation. Without intelligent and diligent attention to these points, no chemical treatment will give maximum benefits. With soils severely affected with black alkali, failure to observe these precautions may make the difference between success and failure.

SUMMARY

Alkali soils contain either an excess of soluble salts or of absorbed sodium. Reclamation depends upon the removal of these excesses.

Good drainage is essential to success in alkali reclamation. Soluble

salts accumulate in low places in arid regions and arise in soils from the subsoil chiefly through the agency of water. They can be removed from soils only through the agency of water. There is very little movement of salts in soils which contain no free water, but free water moves upward in soils by capillarity, carrying the dissolved salts with it. If evaporation takes place in that part of the soil which is kept moist by capillarity, soluble salts will accumulate; therefore the water table should be kept well below the root zone. Unless this is done the benefits of reclamation measures will be temporary only.

Black-alkali soils contain both soluble carbonate and absorbed sodium. If the drainage conditions are favorable these constituents can be removed by applying the proper amount of gypsum, sulfur, iron sulfate, or alum, and then leaching. Extensive investigations at Fresno have demonstrated that, among the materials just mentioned, sulfur is the most economical. The application of 1,000 pounds per acre has produced equally as good results as larger amounts. Gypsum, iron sulfate, and alum were also effective, but the cost was higher than for sulfur. In localities where gypsum, iron sulfate, or alum can be purchased cheaply, it is possible that the use of any one of them might be preferable to that of sulfur.

The effect of sulfur is dependent upon its oxidation and, since the oxidation of sulfur in soils is caused by microörganisms, several months are required for maximum effects. The Fresno soil is able to produce the necessary oxidation of sulfur without artificial inoculation. There appears to be no important difference in the effectiveness of inoculated and uninoculated sulfur, or between colloidal or extremely finely ground forms and comparatively coarse sulfur. Therefore, the least expensive form of sulfur should be purchased for alkali-soil treatment.

Although the cost of sulfur treatment is economically feasible with the Fresno soil, a still less expensive and equally effective method of reclamation is available. It was found that by encouraging the growth of Bermuda grass and irrigating frequently for two summers, the alkali conditions were effectively overcome. It is probable that the growth of some alkali-resistant legume, such as *Melilotus alba,* under similar irrigation conditions, will be as effective and possibly more so. In climates not favorable for Bermuda grass, it has been found that the growth of other grasses and legumes can be utilized to good advantage.

The application of manure in conjunction with the growth of Bermuda grass, or of other alkali-resistant plants, will probably be a valuable aid to reclamation.

White-alkali soils can be readily reclaimed by drainage and leaching

without the application of any soil amendment whatever. The principal abnormality to be overcome in white-alkali soils is the excess of salts which they contain. Drainage and leaching, if applied systematically, will accomplish this end effectively, provided the subsoil is not too dense.

Neither the application of gypsum, sulfur, or other chemicals, nor the growing of alkali-resistant plants, like Bermuda grass and species of *Melilotus,* is an effective substitute for good farming and soil-management methods. Special care and effort are required to grow crops successfully on alkali soils. Each irrigation check should be carefully leveled in order that water can be applied uniformly. The moisture conditions of the soil at the time of seeding should be as nearly optimum as possible, in order to insure germination without the necessity of irrigation. After alfalfa has germinated, irrigation water should be applied at frequent intervals for a period of several weeks. The object should be to keep the soil solution diluted as much as possible and to leach the soluble salts downward to some extent each time irrigation water is applied. Special care should be taken to avoid scalding during periods of hot weather. The intelligent use of these measures will greatly aid in the reclamation process. Without them failure or mediocre success is likely to result.

The results of these investigations show definitely that it is economically feasible to reclaim almost any alkali soil provided it can be effectively drained and an adequate supply of irrigation water is available.

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LITERATURE CITED

[1] BURGESS, P. S.
1928. Alkali soil studies and methods of reclamation. Arizona Agr. Exp. Sta. Bul. 123:157–81.

[2] EATON, FRANK M.
1935. Boron in soils and irrigation waters and its effect on plants, with particular reference to the San Joaquin Valley of California. U. S. Dept. Agr. Tech. Bul. 448:1–131.

[3] HILGARD, E. W.
1907. Soils. 593 p. The Macmillan Co., New York City.

[4] JOHNSTON, W. W., and W. L. POWERS.
1924. A progress report of alkali land reclamation investigations in eastern Oregon. Oregon Agr. Exp. Sta. Bul. 210:1–27.

[5] KELLEY, W. P., and ALEXANDER ARANY.
1928. The chemical effect of gypsum, sulfur, iron sulfate, and alum on alkali soil. Hilgardia 3(14):393–420.

[6] KELLEY, W. P., and S. M. BROWN.
1934. Principles governing the reclamation of alkali soils. Hilgardia 8(5):149–77.

[7] KELLEY, W. P., and E. E. THOMAS.
1920. The effects of alkali on citrus trees. California Agr. Exp. Sta. Bul. 318: 305–37. (Out of print.)

[8] KELLEY, W. P., and E. E. THOMAS.
1928. Reclamation of the Fresno type of black-alkali soil. California Agr. Exp. Sta. Bul. 455:1–37. (Out of print.)

[9] KNIGHT, E. W.
1935. Agricultural investigations on the Newlands (Nev.) reclamation project. U. S. Dept. Agr. Tech. Bul. 464:1–35.

[10] MCGEORGE, W. T., and R. A. GREENE.
1935. Oxidation of sulphur in Arizona soils and its effect on soil properties. Arizona Agr. Exp. Sta. Tech. Bul. 59:297–325.

[11] SCOFIELD, CARL S.
1924. The movement of water in irrigated soils. Jour. Agr. Research 27:617–93.

[12] SCOFIELD, CARL S., and FRANK B. HEADLEY.
1921. Quality of irrigation water in relation to land reclamation. Jour. Agr. Research 21:265–78.

[13] 'SIGMOND, ALEXIUS A. J. DE
1927. Hungarian alkali soils and methods of their reclamation. 156 p. California Agr. Exp. Sta. Spec. Pub. (Out of print.)

[14] THOMAS, EDWARD E.
1936. Reclamation of white-alkali soils in the Imperial Valley. California Agr. Exp. Sta. Bul. 601:1–15.

[15] THOMAS, EDWARD E.
1936. Reclamation of black-alkali soils with various kinds of sulfur. Hilgardia 10(5):127–42.

[16] WURSTEN, J. L., and W. L. POWERS.
1934. Reclamation of virgin black alkali soils. Jour. Amer. Soc. Agron. 26: 752–62.

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